Photo-nuclear collisions in PYTHIA 8

UPC 2023: INTERNATIONAL WORKSHOP ON THE PHYSICS OF ULTRA PERIPHERAL COLLISIONS

Ilkka Helenius
December 15th, 2023
Motivation: data for inclusive $\gamma$-p and $\gamma$-Pb from UPCs at the LHC

$(\text{Pb }\to \gamma)+\text{p}$: [CMS: Murillo Quijada, QM2022]

- Multiplicity distribution well in line for $\gamma$-p but $\gamma$-p not enough for $\gamma$-Pb

$(\text{Pb }\to \gamma)+\text{Pb}$: [ATLAS: PRC 104, 014903 (2021)]
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(Pb $\rightarrow \gamma$)+p: [CMS: Murillo Quijada, QM2022]

- Multiplicity distribution well in line for $\gamma$-p but $\gamma$-p not enough for $\gamma$-Pb
- CMS $\gamma$-p $v_2$ reproduced with Pythia, ATLAS data show finite $v_2$ and $v_3$ in $\gamma$-Pb

(Pb $\rightarrow \gamma$)+Pb: [ATLAS: PRC 104, 014903 (2021)]
PYTHIA 8: A general purpose event generator

- Latest release 8.310 (July 2023)
- A new physics manual for 8.3

[SciPost Phys. Codebases 8-r8.3 (2022)]

Outline

1. Pythia 8 basics
2. Photoproduction in e+p at HERA
3. UPCs at the LHC
   - Photon fluxes in Pythia
   - Photon-ion collisions
   - $v_2$ extraction
4. Summary & Outlook

[figure by P. Skands]
Physics modelled within PYTHIA 8

Classify event generation in terms of “hardness”

1. Hard Process (here $t\bar{t}$)
Physics modelled within PYTHIA 8

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3. Matching, Merging and matrix-element corrections

[figure credit: P. Skands]
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[figure credit: P. Skands]
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5. Parton showers:
   - ISR, FSR, QED, Weak

[figure credit: P. Skands]
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6. Hadronization, Beam remnants

[figure credit: P. Skands]
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2. Resonance decays ($t, Z, \ldots$)
3. Matching, Merging and matrix-element corrections
4. Multiparton interactions
5. Parton showers: ISR, FSR, QED, Weak
6. Hadronization, Beam remnants
7. Decays, Rescattering

[figure credit: P. Skands]
Photoproduction in HERA
Electron-proton collisions and connection to UPCs

Classified in terms photon virtuality $Q^2$

Deep inelastic scattering (DIS)
- High virtuality, $Q^2 > \text{a few GeV}^2$
- Lepton scatters off a parton by exchanging a highly virtual photon

Photoproduction (PhP)
- Low virtuality, $Q^2 \rightarrow 0 \text{ GeV}^2$
  $\Rightarrow$ Similar to UPCs
- Photon may fluctuate into a hadronic state, resolved in the interaction
- Hard scale $\mu$ provided by the final state
Photon structure at $Q^2 \approx 0 \text{ GeV}^2$

Partonic structure of resolved (anom. + VMD) photon encoded in photon PDFs

$$f_i^\gamma(x_\gamma, \mu^2) = f_i^{\gamma, \text{dir}}(x_\gamma, \mu^2) + f_i^{\gamma, \text{anom}}(x_\gamma, \mu^2) + f_i^{\gamma, \text{VMD}}(x_\gamma, \mu^2)$$

- $f_i^{\gamma, \text{dir}}(x_\gamma, \mu^2) = \delta_{i\gamma} \delta(1 - x_\gamma)$
- $f_i^{\gamma, \text{anom}}(x_\gamma, \mu^2)$: Perturbatively calculable
- $f_i^{\gamma, \text{VMD}}(x_\gamma, \mu^2)$: Non-perturbative, fitted or vector-meson dominance (VMD)

Factorized cross section

$$d\sigma^{bp \to kl + X} = f_b^p(x) \otimes f_j^\gamma(x_\gamma, \mu^2) \otimes f_i^p(x_p, \mu^2) \otimes d\sigma^{ij \to kl}$$
Evolution equation and ISR for resolved photons

ISR probability based on DGLAP evolution

• Add a term corresponding to $\gamma \rightarrow q\bar{q}$ to (conditional) ISR probability

$$dP_{a \leftarrow b} = \frac{dQ^2}{Q^2} \frac{\alpha_s}{2\pi} \frac{x' f'_a(x', Q^2)}{x f'_b(x, Q^2)} P_{a \rightarrow bc}(z) dz + \frac{dQ^2}{Q^2} \frac{\alpha_{em}}{2\pi} \frac{e_b^2}{e_b^r} P_{\gamma \rightarrow bc}(x)$$

• Corresponds to ending up to the beam photon during evolution

$\Rightarrow$ Parton originated from the point-like (anomalous) part of the PDFs

• No further ISR or MPIs below the scale of the splitting

• Implemented only for Simple Shower in PYTHIA
Comparison to HERA dijet photoproduction data

ZEUS dijet measurement

- $Q^2 < 1.0 \text{ GeV}^2$
- $134 < W_{\gamma p} < 277 \text{ GeV}$
- $E_{T}^{\text{jet1}} > 14 \text{ GeV}$, $E_{T}^{\text{jet2}} > 11 \text{ GeV}$
- $-1 < \eta_{\text{jet1,2}} < 2.4$

Two contributions

- Momentum fraction of partons in photon
  \[ x_{\gamma}^{\text{obs}} = \frac{E_{T}^{\text{jet1}}e^{\eta_{\text{jet1}}} + E_{T}^{\text{jet2}}e^{\eta_{\text{jet2}}}}{2yE_{e}} \approx x_{\gamma} \]
- Sensitivity to process type

Comparison to HERA dijet photoproduction data

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  \[ x_{\gamma}^{\text{obs}} = \frac{E_{T}^{\text{jet}1} e^{\eta^{\text{jet}1}} + E_{T}^{\text{jet}2} e^{\eta^{\text{jet}2}}}{2yE_e} \approx x_{\gamma} \]

- Sensitivity to process type

- At high-$x_{\gamma}^{\text{obs}}$ direct processes dominate
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

Pseudorapidity

- Data well reproduced
- Not sensitive to MPI modelling ($p_{T,0}$)

$P_{T,0} = 3\text{ GeV}$

$P_{T,0} = 4\text{ GeV}$

$N_{ch} > 20$

MC/Data

[ZEUS: JHEP 12 (2021) 102]
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

Pseudorapidity

- Data well reproduced
- Not sensitive to MPI modelling ($p_{T,0}$)

Multiplicity

- Sensitivity to MPI parameters, clear support for MPIs
- Data within $p_{T,0}$ variations
- Good baseline to study $\gamma + A$ in UPCs

[ZEUS: JHEP 12 (2021) 102]
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

**Pseudorapidity**

- Data well reproduced
- Not sensitive to MPI modelling ($p_{T,0}$)

**Multiplicity**

- Sensitivity to MPI parameters, clear support for MPIs
- Data within $p_{T,0}$ variations
- Good baseline to study $\gamma+A$ in UPCs
- Direct contribution negligible in high-multiplicity events ($N_{ch} > 20$)

⇒ Focus on resolved processes
Photon fluxes in PYTHIA 8
Photon fluxes from Equivalent Photon Approximation (EPA)

- In case of a point-like lepton we have (neglecting electron mass)

\[
f_{\gamma}^l(x, Q^2) = \frac{\alpha_{\text{em}}}{2\pi} \frac{1}{Q^2} \frac{(1 + (1 - x)^2)}{x}
\]

- For protons need to include form factors, using dipole form factor

\[
f_{\gamma}^p(x, Q^2) = \frac{\alpha_{\text{em}}}{2\pi} \frac{x}{Q^2} \frac{1}{(1 + Q^2/Q_0^2)^4} \left[ \frac{2(1 + \mu_p \tau)}{1 + \tau} \left( \frac{1 - x}{x^2} - \frac{M_p^2}{Q^2} \right) + \mu_p^2 \right]
\]

where \( \tau = Q^2/4M_p^2 \), \( \mu_p = 2.79 \), \( Q_0^2 = 0.71 \text{ GeV}^2 \)

- Drees-Zeppenfeld approximation \((M_p = 0, \mu_p = 1)\)

\[
f_{\gamma}^p(x, Q^2) = \frac{\alpha_{\text{em}}}{2\pi} \frac{1}{Q^2} \frac{1}{(1 + Q^2/Q_0^2)^4} \frac{(1 + (1 - x)^2)}{x}
\]

\(\Rightarrow\) Large \(Q^2\) suppressed wrt. leptons \(\Rightarrow\) photoproduction

- In ME generators (such as MG5) integrated over \(Q^2\) and assumed collinear
Define your own photon flux for PYTHIA 8

- Derive a new object from PDF class

```cpp
class Proton2gammaEPA : public PDF {

public:

    // Constructor.
    Proton2gammaEPA(int idBeamIn) : PDF(idBeamIn) {}

    // Update the photon flux.
    void xFUpdate(int, double x, double Q2) {

        double m2proton = pow2(0.938);
        double mup2 = pow2(2.79);
        double Q20 = 0.71;
        double FQ4 = 1. / pow4(1 + Q2 / Q20);
        double coupling = 0.5 * 0.007297353080 / M_LI * FQ4;
        double tau = Q2 / (4. * m2proton);
        xgamma = coupling * (pow2(x) / Q2) * (2. * (1. + mup2*tau) / (1. + tau) *
          (1 - x)/pow2(x) - m2proton / Q2) + mup2;
    }
};
```

- Pass as a pointer to PYTHIA

```cpp
pythia.readString("PDF:beamA2gamma = on");
pythia.readString("PDF:beamB2gamma = on");
pythia.readString("PDF:proton2gammaSet = 0");
PDFPtr photonFluxA = make_shared<Proton2gammaEPA>(2212);
PDFPtr photonFluxB = make_shared<Proton2gammaEPA>(2212);
pythia.setPhotonFluxPtr(photonFluxA, photonFluxB);
```

Example in p-p: $\gamma\gamma \rightarrow \mu^+\mu^-$

- No finite-size effects accounted

• Large impact parameter \((b \gtrsim 2R_A)\)
  \(\Rightarrow\) No strong interactions

• Large flux due to large EM charge of nuclei
  \(\Rightarrow\) \(\gamma\gamma\) and \(\gamma A\) collisions

• With heavy nuclei use \(b\)-integrated point-like-charge flux

\[
f_A^\gamma(x) = \frac{2\alpha_{EM}Z^2}{\pi x} \left[ \xi K_1(\xi)K_0(\xi) - \frac{\xi^2}{2} \left(K_1^2(\xi) - K_0^2(\xi)\right) \right]
\]

where \(\xi = b_{\text{min}} x m\) where \(b_{\text{min}}\) reject nuclear overlap, \(Q^2 \ll 1 \text{ GeV}^2\)
Ultraperipheral heavy-ion collisions

- Large impact parameter \((b \gtrsim 2R_A)\)
  ⇒ No strong interactions
- Large flux due to large EM charge of nuclei
  ⇒ \(\gamma\gamma\) and \(\gamma A\) collisions

- With heavy nuclei use \(b\)-integrated point-like-charge flux

\[
f^A_\gamma(x) = \frac{2\alpha_{\text{EM}} Z^2}{x \pi} \left[ \xi K_1(\xi) K_0(\xi) - \frac{\xi^2}{2} (K_1^2(\xi) - K_0^2(\xi)) \right]
\]

where \(\xi = b_{\text{min}} x m\) where \(b_{\text{min}}\) reject nuclear overlap, \(Q^2 \ll 1\text{ GeV}^2\)
Dijets in ultra-peripheral heavy-ion collisions

- Pythia setup with nucleon target only ⇒ Not a realistic background for jet reconstruction
- Good agreement out of the box when accounting both direct and resolved
- Also EM nuclear break-up significant
Photon-ion collisions
Aim to simulate high-multiplicity events

- Dominated by resolved photons
  - Set up an explicit VMD model with linear combination of vector-meson states ($\rho$, $\omega$, $\phi$ and $J/\psi$)
  - Use VM PDFs from SU21
    [Sjöstrand, Utheim; Eur.Phys.J.C 82 (2022) 1, 21]
  - Cross sections from SaS
    [Schuler, Sjöstrand; Phys.Rev.D 49 (1994) 2257-2267]
  - Sample collision energy from flux
    - VMD-nucleon scatterings
Modelling $\gamma$-$A$ with Pythia

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  - [Sjöstrand, Uttheim; Eur.Phys.J.C 82 (2022) 1, 21]
- Cross sections from SaS
  - [Schuler, Sjöstrand; Phys.Rev.D 49 (1994) 2257-2267]
- Sample collision energy from flux
  - In line with the full photoproduction
Angantyr model for heavy ions in Pythia

[Bierlich, Gustafson, Lönnblad, Shah; JHEP 10 (2018) 134]

- Monte Carlo Glauber to sample nucleon configurations
- Cross section fluctuations, fitted to partial nucleon-nucleon cross sections
- Secondary (wounded) collisions as diffractive excitations
- Can now handle generic hadron-ion and varying energy [I.H., Utheim; in progress]

⇒ VMD-nucleus scatterings
Comparison with data for $\gamma$+A (preliminary)

- ATLAS data not corrected for efficiency, estimated with $N_{ch}^{rec} \approx 0.8 \cdot N_{ch}$
- Relative increase in multiplicity well in line with the VMD-Pb setup
Comparison with data for $\gamma + A$ (preliminary)

- Multiplicity cut adjusted according to the limited efficiency
- Good description of the measured rapidity distribution with the VMD-Pb setup
Two-particle correlations in ATLAS analysis

- ATLAS apply template-fitting method to extract $v_n$ from two-particle correlations
  - Perform a Fourier fit to obtain $c_n$’s for low-multiplicity events (nonflow?)

$$
\gamma^{LM}(\Delta \phi) = c_0 + 2 \cdot \sum_{n=1}^{4} c_n \cos(n \Delta \phi)
$$

- Fit high multiplicity $v_{n,n}$’s on top

$$
\gamma^{HM}(\Delta \phi) = F \cdot \gamma^{LM}(\Delta \phi) + G \left[ 1 + 2 \cdot \sum_{n=2}^{4} v_{n,n} \cos(n \Delta \phi) \right]
$$

Free parameters $c_n, v_{n,n}, F, G$
- Can now repeat the fit with Pythia results
Template fit to Pythia simulations

- **Template fit**
  - $v_{2,2} = 0.00245$
  - $v_{3,3} = -0.00032$
  - $v_{4,4} = 0.00006$

- **Fourier fit**
  - $v_{2,2} = 0.00245$
  - $v_{3,3} = -0.00032$
  - $v_{4,4} = 0.00006$

**Pythia 8**

- $15 < N_{\text{ch}}^{\text{rec}} < 20$

- $20 < N_{\text{ch}}^{\text{rec}} < 30$

- Template fit $G + F*Y_{lm}$

- Ratio graphs:
  - **Template fit**: $0.95 < \text{ratio} < 1.00$
  - **Pythia 8**: $0.95 < \text{ratio} < 1.00$
Comparison to ATLAS $v_n$ data

- Simulated results in line with the direct Fourier fit for $v_{2,2}$
- Consistent with zero after template fitting (non-flow subtraction)
- String interactions in high-multiplicity hadronization, hadronic rescattering?
Summary & Outlook

Summary

• In e+p validated setup for photoproduction at HERA
• Includes fluxes relevant for proton and heavy-ion UPCs
• First steps for full $\gamma + A$ (8.311)
  ⇒ In line with multiplicity distributions
  ⇒ As such not consistent with finite $v_2$

Outlook

• Include full photon structure
• Study different string-interaction effects for high-multiplicity events
Backup slides
PYTHIA Collaboration

- Christian Bierlich (Lund University)
- Naomi Cooke (University of Glasgow)
- Nishita Desai (TIFR, Mumbai)
- Leif Gellersen (Lund University)
- Ilkka Helenius (University of Jyväskylä)
- Philip Ilten (University of Cincinnati)
- Leif Lönnblad (Lund University)
- Stephen Mrenna (Fermilab)
- Christian Preuss (ETH Zurich)
- Torbjörn Sjöstrand (Lund University)
- Peter Skands (Monash University)
- Marius Utheim (University of Jyväskylä)
- Rob Verheyen (University College London)
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Codemaster
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https://pythia.org
authors@pythia.org
DGLAP equation for photons

- Additional term due to $\gamma \rightarrow q\bar{q}$ splittings

$$\frac{\partial f_i^\gamma(x, Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{em} e_i^2}{2\pi} P_i^\gamma(x) + \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z) f_j(x/z, Q^2)$$

where $P_i^\gamma(x) = 3 \left( x^2 + (1 - x)^2 \right)$ for quarks, 0 for gluons (LO)

- Resulting PDFs has point-like (or anomalous) and hadron-like components

$$f_i^\gamma(x, Q^2) = f_i^{\gamma, pl}(x, Q^2) + f_i^{\gamma, had}(x, Q^2)$$

- $f_i^{\gamma, pl}$: Calculable from perturbative QCD
- $f_i^{\gamma, had}$: Requires non-perturbative input fixed in a global analysis
Photon structure at $Q^2 \sim 0 \text{ GeV}^2$

Linear combination of three components

$$|\gamma\rangle = c_{\text{dir}}|\gamma_{\text{dir}}\rangle + \sum_q c_q|q\bar{q}\rangle + \sum_V c_V|V\rangle$$

where the last term includes a linear combination of vector meson states up to $J/\Psi$

$$c_V = \frac{4\pi\alpha_{\text{EM}}}{f_V^2}$$

<table>
<thead>
<tr>
<th>$V$</th>
<th>$f_V^2/(4\pi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0$</td>
<td>2.20</td>
</tr>
<tr>
<td>$\omega$</td>
<td>23.6</td>
</tr>
<tr>
<td>$\phi$</td>
<td>18.4</td>
</tr>
<tr>
<td>$J/\Psi$</td>
<td>11.5</td>
</tr>
</tbody>
</table>
Equivalent photon approximation

Compare to full calculation

• Example process $pp \rightarrow \gamma\gamma \rightarrow \mu^+\mu^-$
• Different approximations (e.g.) by Drees and Zeppenfeld $\sim 20\%$ difference to full calculation
• Keeping finite mass and correct magnetic moment provides $\sim$ few percent accuracy
• Not checked for other observables, such as acoplanarity

Figure 8. Same as Figure 7, but at $\sqrt{s} = 13$ TeV.

[S. Yrjänheikki, MSc thesis]
Photon fluxes in PYTHIA 8

- Enable $\gamma+p$ in $e+p$
- Enable $\gamma+p$ in $p+p$
- Enable $\gamma+p$ in Pb+$p$

```python
pythia.readString("Beams:idA = -11");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
```
Photon fluxes in PYTHIA 8

- Enable $\gamma+p$ in $e+p$
  
  ```python
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  pythia.readString("Beams:idB = 2212");
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  ```

![Graph showing photon fluxes in PYTHIA 8]
Photon fluxes in PYTHIA 8

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pythia.readString("PDF:beamA2gamma = on");
```

- Enable $\gamma+p$ in $p+b$

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pythia.readString("Beams:idA = 2212");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
pythia.readString("PDF:proton2gammaSet = 0");
pythia.readString("PDF:beam2gammaApprox = 2");
pythia.readString("Photon:sampleQ2 = off");
PDFPtr photonFlux = make_shared<Nucleus2gamma>(2212);
pythia.setPhotonFluxPtr(photonFlux, 0);
```

For more examples see `main68.cc`, `main69.cc`, `main70.cc`, `main78.cc` in examples directory.
Photon fluxes in PYTHIA 8

- Not enough? Define your own flux

```
class Nucleus2gamma2 : public PDF {
public:

    // Constructor.
    Nucleus2gamma2(int idBeamIn) : PDF(idBeamIn) {}

    // Update the photon flux.
    void xfUpdate(int, double x, double ) {
        // Minimum impact parameter (-2*radius) [fm].
        double bmin = 2 * 6.636;

        // Charge of the nucleus.
        double z = 82.;

        // Per-nucleon mass for lead.
        double m2 = pow2(0.9314);
        double alphaEM = 0.007297353080;
        double hbarc = 0.197;
        double xi = x * sqrt(m2) * bmin / hbarc;
        double bk0 = besselK0(xi);
        double bk1 = besselK1(xi);
        double intB = xi * bk1 * bk0 - 0.5 * pow2(xi) * ( pow2(bk1) - pow2(bk0) );
        xgamma = 2. * alphaEM * pow2(z) / M_Pi * intB;
    }
};
```

[from main70.cc]
An example process: $\gamma\gamma \rightarrow \mu^+\mu^-$

- Can take place in EE, SD and DD (also DY processes with resolved photons?)
- Implemented natively in Pythia, can also generate with an ME generator (MG5, SC)

**EE contribution**
- Clean process to study fluxes
- However, fluxes only does not account for finite-size effects

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- Implemented natively in Pythia, can also generate with an ME generator (MG5, SC)

EE contribution
- Clean process to study fluxes
- However, fluxes only does not account for finite-size effects
- Not quite back-to-back due to
  - $p_T$ generated by non-collinear photons
  - QED radiation in the final state
- Acoplanarity $|\pi - \Delta \phi|$ quantify the effect

- Needed to tune Pythia primordial $k_T$ parameters for external events
- Can use (user-defined) flux for $Q^2$ sampling
Heavy-ion collisions

• Angantyr in Pythia provides a full heavy-ion collisions framework
  [Bierlich, Gustafson, Lönnblad & Shah: 1806.10820]

• Hadronic rescattering can be included as well, enhances collective effects
Angantyr can be applied also to asymmetric p+A collisions
The centrality measure well reproduced
Similarly centrality-dependent multiplicities
ATLAS data for $v_n$ in $\gamma$+Pb

- Non-zero flow coefficients also for $\gamma$+Pb
- Expected baseline from MC simulations?
Comparison with data for $\gamma+A$ (preliminary)

- Pythia8 $\gamma+p$ in ATLAS result should correspond to gm-p on right
- Relative increase in multiplicity well in line with the VMD setup
Comparison with data for $\gamma+A$ (preliminary)

![Comparison graph]

- Pythia8 $\gamma+p$ in ATLAS result should correspond to gm-$p$ on right
- Relative increase in multiplicity well in line with the VMD setup
Comparison with data for $\gamma+A$ (preliminary)

- Pythia8 $\gamma+p$ in ATLAS result should correspond to gm-p on right
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr
Comparison with data for $\gamma+A$ (preliminary)

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- Relative shift in rapidity distribution in line with the VMD setup using Angantyr
Comparison with data for $\gamma+A$ (preliminary)

- $\Sigma_\gamma \Delta \eta$: Sum of rapidity gaps for which $\Delta \eta > 0.5$
- Similar for $\gamma$-p and $\gamma$-Pb
Role of cross section fluctuations

- High-multiplicity tail less pronounced with Angantyr:CollisionModel = 0 with fixed nucleon radius, ATLAS data seem to favour fluctuations
Energy distributions vs. multiplicity

\[ \langle W_{\gamma\text{Pb}} \rangle \approx 150 \]

\[ \langle W_{\gamma\text{Pb}} \rangle \approx 470 \]

\[ \langle W_{\gamma\text{Pb}} \rangle \approx 570 \]